to appear in the Astrophysical Journal, Letters
Preprint typeset using LaTeX style emulateapj v. 11/12/01

DETECTION OF TWO-ARMED SPIRAL SHOCKS ON THE ACCRETION DISK OF THE ECLIPSING FAST NOVA V1494 AQUILAE

Izumi Hachisu
Department of Earth Science and Astronomy, College of Arts and Sciences, University of Tokyo, Komaba, Meguro-ku, Tokyo 153-8902, Japan
hachisu@chianti.c.u-tokyo.ac.jp

Mariko Kato
Department of Astronomy, Keio University, Hiyoshi, Kouhoku-ku, Yokohama 223-8521, Japan
mariko@educ.cc.keio.ac.jp

and

Taichi Kato
Department of Astronomy, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan
tkato@kusastro.kyoto-u.ac.jp

to appear in the Astrophysical Journal, Letters

ABSTRACT

We have modeled the unusual orbital light curve of V1494 Aquilae (Nova Aquilae 1999 No.2) and found that such an unusual orbital light curve can be reproduced when there exist two-armed, spiral shocks on the accretion disk. V1494 Aql is a fast classical nova and found to be an eclipsing system with the orbital period of 0.1346138 days in the late phase of the nova outburst. Its orbital light curve shows a small bump at orbital phase 0.2, a small dip at 0.3, sometimes a small bump at 0.4, and a large bump at $0.6-0.7$ outside eclipse. Such a double- or triple-wave pattern outside eclipse has never been observed even though overall patterns look like some supersoft X-ray sources or eclipsing polars. We have calculated orbital light curves including the irradiation effects of the accretion disk and the companion by the hot white dwarf. These unusual patterns can be reproduced when we assume two-armed spiral shocks on the accretion disk. Especially, triple-wave patterns are naturally obtained. This result strongly suggests the existence of two-armed spiral shocks on the accretion disk in the late phase of the nova outburst.

Subject headings: accretion: accretion disks — binaries: close — binaries: eclipsing — novae, cataclysmic variables — stars: individual (V1494 Aquilae)

1. INTRODUCTION

Angular momentum transport plays an essential role in accretion disks of cataclysmic variables. Two mechanisms have been proposed so far: one is the turbulent viscosity as adopted in the standard accretion disk model of Shakura & Sunyaev (1973) and the other is the direct dissipation by tidal spiral shocks on the accretion disk as first demonstrated by Sawada, Matsuda, & Hachisu (1986). The turbulent viscosity is a local physical process while the tidal spiral shocks have a global structure on the accretion disk. Therefore, we have a chance to observe a global spiral shock structure when they play an essential role in the angular momentum transport of the accretion disk. Such an observational evidence first came from the Doppler maps of the dwarf nova IP Peg outburst (e.g., Steeghs, Harlaftis, & Horne 1997). We have long believed that tidal spiral structures can be detected even in orbital light curves of cataclysmic variables if the spiral patterns are prominent. At last we find such an evidence of spiral patterns on the accretion disk from the orbital light curves of V1494 Aquilae.

V1494 Aquilae (Nova Aquilae 1999 No.2) was discovered by A. Pereira on 1999 December 1.785 UT at $m_V \sim 6.0$ (Pereira et al. 1999). It reached the visual maximum brightness of $m_V \sim 4.0$ on Dec 3.4 UT (t_0 =JD 2,451,515.9±0.1) and decayed at the rate of $t_2 = 6.6 \pm 0.5$ days and $t_3 = 16 \pm 0.5$ days (Kiss & Thomson 2000). Early phase spectra were taken by Fujii (1999) and Ayani (1999), which show P-Cyg profiles of hydrogen Balmer lines with a blueshifted component of 1020 km s^{-1} and 1200 km s^{-1}, respectively. Thus, V1494 Aql has been classified as a fast nova. Kato et al. (2004) have summarized overall development of the V1494 Aql light curve until autumn of 2003 (for about 3 years). Detailed spectral features have been reported by Iijima & Esenoglu (2003).

A short-term periodic modulation was first reported by Novak et al. (2000), who found 0.03 mag variations with a period of 0.0627 days from their 2000 June observation. Retter et al. (2000) analyzed 31 nights of CCD photometry during 2000 June-August and suggested a periodicity of 0.13467(2) days. The full amplitude of the variation in the R-band increased from 0.03 mag in June to 0.07 mag in August. Their folded light curve shows a double-wave structure with a shallower dip at phase 0.5, with about half the amplitude of the main periodicity. Bos et al. (2001) reported, based on unfiltered and R-band CCD photometry obtained on 12 nights during 2001 June-July, a robust change in the shape and amplitude of the 0.13467 days period. It had an eclipse shape with depth about 0.5 mag. A second shallow eclipse (about 0.1 mag deep) at phase 0.5 can be seen. Barsukova & Goranskii (2003) refined, based on V-band photometry during June and September

of 2002, the orbital period of 0.1346141(5) days. They pointed out that the orbital light curve is quite unusual in the sense that it is not similar to ordinary cataclysmic variables with a hot spot on the accretion disk. Pavlenko, Dudka, & Baklanov (1999) made a multicolor photometry and concluded that the eclipse depth is deeper in longer wave lengths (deeper in I-band than in V-band). Pavlenko et al. (1999) further discussed that such an eclipsing characteristic (deeper in longer wave lengths) cannot be explained by the accretion disk or the irradiation effect of the companion because these two light sources have the opposite nature (deeper in short wave lengths). Thus, they suggested, as a model of V1494 Aql orbital light curve, a self eclipsing accretion column in a magnetic polar.

Kato et al. (2004) provided a time-development of the orbital light curves among 2001 November-December, 2002 August, and 2003 June. It sometimes shows a triple-wave structure as well as a double-wave structure. Kato et al. suggested that some structures (probably on the accretion disk) fixed in the binary rotational frame are responsible for the orbital light curve because of the stability of out-of-eclipse light curve patterns. Very recently, Kiss, Csák, & Derekas (2004) pointed out that a close companion to V1494 Aql (located 1.″4 southwest) is brighter than V1494 Aql itself in the very late phase of the outburst. They corrected the brightness of the orbital light curve and found that the depth of the eclipse is about twice deeper in magnitudes than before correction.

The depth of the primary eclipse of V1494 Aql has become deeper as the nova decayed. Such a feature was also observed in the recurrent nova CI Aql 2000 outburst (e.g., Matsumoto et al. 2001), in which the irradiation of the accretion disk plays an essential role (Hachisu & Kato 2003a). Therefore, we expect the accretion disk in V1494 Aql is also responsible for the unusual wavy structure of the orbital light curve. In this Letter, we model the orbital light curve. Almost the same orbital light curve model as in the supersoft X-ray sources is adopted (e.g., Schandl, Meyer-Hofmeister, & Meyer 1997; Hachisu & Kato 2003b,c), which includes the irradiation effects of the accretion disk and of the companion. In addition, we assume two-armed spiral structures on the accretion disk to reproduce a triple-wave structure outside eclipse. In §2, our numerical model for V1494 Aql is briefly introduced and summarized. The numerical results are given in §3. Discussion follows in §4.

2. THE LIGHT CURVE MODEL

Our binary model is illustrated in Figure 1, which consists of a 0.3 $M_\odot$ main-sequence star (MS) filling its Roche lobe, a 1.0 $M_\odot$ white dwarf (WD), and a disk around the WD. The mass of the WD is roughly estimated from the decline rate of the decay phase (e.g., Hachisu et al. 2000; Hachisu & Kato 2001a,b), details of which will be published elsewhere. The mass of the companion is estimated from the mass-period relation for cataclysmic variables (e.g., Patterson 1984; Warner 1995). A circular orbit is assumed. Its ephemeris has recently been refined by Kato et al. (2004). We use this ephemeris, i.e.,

$$t(\mathrm{BJD}) = 2,452,458.3230 + 0.1346138 \times E, \qquad (1)$$

at eclipse minima.

We also assume that the surfaces of the WD, the MS companion, and the accretion disk emit photons as a blackbody at a local temperature which varies with position. For the basic structure of the accretion disk, we assume an axi-symmetric structure with the size and thickness of

$$R_{\mathrm{disk}} = \alpha R_1^*, \qquad (2)$$

and

$$h = \beta R_{\mathrm{disk}} \left(\frac{\varpi}{R_{\mathrm{disk}}} \right)^{\nu}, \qquad (3)$$

where R_{disk} is the outer edge of the accretion disk, R_1^* is the effective radius of the inner critical Roche lobe for the WD component, h is the height of the surface from the equatorial plane, and ϖ is the distance on the equatorial plane from the center of the WD. Here, we adopt $\nu = 2$. We obtain our modeled two-armed spiral structures by multiplying h with z_{height}, as defined below:

$$z_1 = \max \left(1, \frac{\xi_1}{\sqrt{(\varpi/R_{\mathrm{disk}} - \exp(-\eta(\phi-\delta)))^2 + \epsilon^2}} \right), \qquad (4)$$

$$z_2 = \max \left(1, \frac{\xi_2}{\sqrt{(\varpi/R_{\mathrm{disk}} - \exp(-\eta(\phi-\delta-\pi)))^2 + \epsilon^2}} \right), \qquad (5)$$

$$z_{\mathrm{height}} = \max(z_1, z_2). \qquad (6)$$

We further have a slope at the disk edge defined by $z - 10(z - 0.25)(\varpi/\ R_{\mathrm{disk}} - 0.9)$ for $0.9 < \varpi/R_{\mathrm{disk}} < 1.0$. The above various disk parameters are assumed to be $\epsilon = 0.1$, $\xi_1 = \xi_2 = 0.40$, $\eta = 0.41$, $\delta = 65°$, $\alpha = 0.8$, $\beta = 0.095$ for the disk shape of Figure 1. Here, ξ_1 and ξ_2 specify the amplitudes of two spirals so that $\xi_1 = \xi_2$ $(= 0.40)$ means just an anti-symmetric structure of spirals with the same height, η determines the inverse of the pitch angle of logarithmic spirals, δ is the position angle of the spirals against the binary components, ϵ denotes the width of the spiral pattern and represents the height of the spiral against the thickness of the disk together with ξ_1 and ξ_2, i.e., $z_{\mathrm{height}} = \max(\xi_1,\ \xi_2)/\epsilon \sim 4$ at the edge of the disk for the disk shape of Figure 1. In our light curve model, we mainly change four parameters, i.e., the disk thickness (β), the inverse of the pitch angle of spirals (η), the position angle (δ), and the heights of two spirals ($\xi_1 = \xi_2$). The other parameters that specify the disk shape are all fixed to be the above values. These parameters are roughly determined to mimic the results of 3D simulation model of accretion disks (e.g. Makita, Miyawaki, & Matsuda 2000).

The luminosity of the WD is assumed to be $750 - 3,000\ L_\odot$ because we do not know the exact WD luminosity at the time of observation. The disk and the companion star are strongly irradiated by the hot WD. The surfaces of the WD, the disk, and the companion star are divided into many patches as shown in Figure 1. Here we assume that each patch emits photons as a blackbody (with a single temperature). Each patch of the disk or of the companion is irradiated by visible (front side) patches of the hot WD. The total luminosity of the irradiated disk and companion is calculated by summing up the contributions from all patches. The irradiation efficiency is the same as that of Schandl et al. (1997), i.e., 50% of the irradiated energy is emitted by photon but the residual 50% is converted into thermal energy of gas. The accretion luminosity of the disk is also numerically included, although its

contribution to the optical light is much smaller than that of the irradiation effect (see discussion of Hachisu & Kato 2001a,b; Hachisu, Kato, & Schaefer 2003). The numerical method adopted here was fully described in Hachisu & Kato (2001b, 2003a,b,c). The inclination angle (i) of the binary is a free parameter that is determined from our light curve fitting. The original temperature of the companion star is assumed to be 3,000 K, but the shape of the orbital light curve is hardly changed even if we take 2,000 K or 4,000 K for the original temperature of the MS companion. The adopted system parameters are summarized in Table 1.

3. NUMERICAL RESULTS

The best fit model is plotted in Figure 2 by a thick solid line. The orbital modulations of V1494 Aql have been reported by several groups. Here, we adopt data of two groups (Kato et al. 2004; Kiss et al. 2004) to fit with our modeled light curves. Kato et al.'s (square) data have been corrected by using Kiss et al.'s (circle) data, because Kato et al.'s original data include the light from the close companion.

We have changed five parameters (β, η, δ, $\xi_1 = \xi_2$, i) independently and calculated the total of $\sim$ 1300 orbital light curves. It takes about 6 hours to calculate one orbital light curve on a 2.4 GHz Pentium 4 processor, because the surface patch elements are 64×128 ($\theta \times \phi$) for the companion surface, $64 \times 128 \times 2$ ($\varpi \times \phi \times$ (up and down sides)) for the disk, and 16×32 ($\theta \times \phi$) for the WD, and the total of 129 steps for one orbital period. We have used 5 CPUs, so that it took the total computation time of about 1600 hours, i.e., $(6 \times 1300)/5$ CPUs. We have found, by the least square method, the best fit model for out-of-eclipse (orbital phase $0.1 - 0.9$), i.e., $\beta = 0.095$, $\eta = 0.41$, $\delta = 65°$, $\xi_1 = \xi_2 = 0.40$, $i = 78.5°$. For the best fit model, we increase the number of patches for the disk up to $128 \times 256 \times 2$ ($\varpi \times \phi \times$ (up and down sides)) in order to calculate a rather smooth light curve. Such a high quality light curve is shown in Figure 2.

The triple-wave structure of out-of-eclipse orbital light curve is reasonably and naturally reproduced with our spiral shock pattern model. Both the thickness of the accretion disk and the pitch angle of spirals adopted here are roughly consistent with the 3D simulations (e.g., Makita et al. 2000). The present results strongly support the two-armed spiral pattern on the accretion disk. We hope a spectroscopic confirmation of this spiral pattern by Doppler maps for V1494 Aql.

4. DISCUSSION

The orbital light curve varies from night to night as shown in Figure 3 of Kato et al. (2004). Such a scatter is also clearly shown in the present Figures 2 and 3 for Kiss et al.'s (2004) data. To reproduce this variation, we have changed parameter ξ_1 and ξ_2 independently (see Fig. 3). The variation appears in orbital phase of $0.1 - 0.3$ and the upper and lower bounds for these variations can be well reproduced by the models of $\xi_1 = 0.26$, $\xi_2 = 0.44$ for the upper bound, and $\xi_1 = 0.44$, $\xi_2 = 0.24$ for the lower bound. Here, ξ_1 and ξ_2 represent the height of the spiral arm in the rear and front side on the disk of Figure 1, respectively. The other parameters are the same as those in Figures 1 and 2.

It is remarkable that the peak at orbital phase ~ 0.65 is rather stable and never disappears. This is consistent with the robustness of the period for the out-of-eclipse shape as emphasized by Kato et al. (2004).

Pavlenko et al. (1999) discussed the main light source for the wavy structures of the out-of-eclipse orbital light curve. They argued, as a light source, (1) accretion disk, (2) ellipsoidal shape of the companion, (3) reflection (irradiation) effect of the companion by the hot white dwarf, (4) intermediate polar activity, and (5) polar activity self-eclipsed by the accretion column. They rejected possibilities (1)-(4) and suggested a viable model of polar activity. Their reasons rejecting possibilities (2) and (4) are reasonable but not for possibilities (1) and (3) as discussed below.

Pavlenko et al. (1999) rejected the possibility of accretion disk by pointing out two reasons: (i) the maximum duration of the eclipse of the disk limited by the Roche lobe size and it cannot exceed a quarter of the orbital phase while the overall duration of the eclipse is as large as 0.45 of the orbital period. (ii) The peak of light emission of the accretion disk lies in the blue region of the spectrum, so that the amplitude of the eclipse should increase as the wavelength becomes shorter ("as the wave length is increased" in their text is mistaken). However, they observed the opposite trend: the amplitude in the red region is much more deeper than in the visual region. As for the first conjecture (i), based on the accretion disk model together with the irradiation effects of the disk and the companion, we have already constructed the orbital light curves that match well the observational data. Second, we should be careful with the above statement (ii) because the depth of the primary eclipse varies from night to night as seen in Figure 3 of Kato et al. (2004) and its depth changes as large as $\Delta R_c \sim 0.4$ between different periods of the observations as shown in Figures 2 and 3. Pavlenko et al.'s (2003) R and I light curves are not simultaneous ones but taken in different periods (R is earlier than I). The V light curve is reconstructed from Barsukova & Goranskii's (2003) data.

They also rejected possibility (3) based on the same statement as (ii) discussed above. However, their multicolor results may simply suggest the fact that the eclipse depth varies from period (night) to period (night). Therefore, we cannot conclude statement (ii) only from the different depths at the different periods.

For the assumed WD luminosity of $L_{\rm WD} = 3,000\ L_\odot$, the distance modulus is obtained to be $(m-M)_R = 12.05$ and the corresponding distance is estimated to be $d \sim 1.4$ kpc (see Table 1). However, this does not mean the real distance to V1494 Aql because we do not know the real luminosity of $L_{\rm WD}$ at the time of the two observations. For instance, if we adopt $L_{\rm WD} = 750\ L_\odot$, the shape of the orbital light curve hardly changes but the distance modulus becomes $(m-M)_R = 11.45$ and $d \sim 1$ kpc.

We thank L. Kiss for providing us their V1494 Aql data.

REFERENCES

Ayani, K. 1999, IAU circ., 7324
Barsukova, E. A., & Goranskii, V. P. 2003, Astronomy Letters, 29, 195
Bos, M., Retter, A., Cook, L., & Novak, R. 2001, IAU Circ., 7665
Fujii, M. 1999, IAU circ., 7324
Hachisu, I., & Kato, M. 2001a, ApJ, 553, L161
Hachisu, I., & Kato, M. 2001b, ApJ, 558, 323
Hachisu, I., & Kato, M. 2003a, ApJ, 588, 1003
Hachisu, I., & Kato, M. 2003b, ApJ, 590, 445
Hachisu, I., & Kato, M. 2003c, ApJ, 598, 527
Hachisu, I., Kato, M., Kato, T., & Matsumoto, K. 2000, ApJ, 528, L97
Hachisu, I., Kato, M., & Schaefer, B. E. 2003, ApJ, 584, 1008
Iijima, T., & Esenoglu, H. H. 2003, A&A, 404, 997
Kato, T., Ishioka, R., Uemura, M., Starkey, D. R., & Krajci, T. 2004, PASJ, in press (astro-ph/0310519)
Kiss, L. L., Csák, B., & Derekas, A. 2004, A&A, 416, 319
Kiss, L. L., & Thomson, J. R. 2000, A&A, 355, L9
Makita, M., Miyawaki, K., & Matsuda, T. 2000, MNRAS, 316, 906
Matsumoto, K., et al. 2001, A&A, 378, 487
Novak, R., Retter, A., Cook, L., Korcakova, D., & Janik, J. 2000, IAU circ., 7448
Patterson, J. 1984, ApJS, 54, 443
Pereira, A., di Cicco, D., Vitorino, C., & Green, D. W. E. 1999, IAU circ., 7323
Pavlenko, E. P., Dudka, O. I., & Baklanov, A. V. 2003, Astrophysics, 46, 191
Rieke, G. H., & Lebofsky, M. J. 1985, ApJ, 288, 618
Retter, A., Cook, L., Novak, R., Saxton, J. M., Jensen, L. T., Korcakova, D., & Janik, J. 2000, IAU Circ., 7537.
Sawada, K., Matsuda, T., & Hachisu, I. 1986, MNRAS, 219, 75
Schandl, S., Meyer-Hofmeister, E., & Meyer, F. 1997, A&A, 318, 73
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Steeghs, D., Harlaftis, E. T., & Horne, K. 1997, MNRAS, 290, L28
Warner, B. 1995, Cataclysmic variable stars, Cambridge, Cambridge University Press

Table 1
Adopted system parameters of V1494 Aquilae

parameter	symbol	present work
inclination angle	i	78.5°
WD mass	$M_{\rm WD}$	$1.0\ M_\odot$
WD luminosity	$L_{\rm WD}$	$750 - 3,000\ L_\odot$
MS mass	$M_{\rm MS}$	$0.3\ M_\odot$
mass accretion rate	$\dot M$	$0.3 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}$
MS temperature	$T_{\rm MS,org}$	3,000 K
distance modulus	$(m-M)_R$	$11.45 - 12.05$
color excess	$E(B-V)$	0.60[a]
R-band absorption	A_R	1.39[b]
distance	d	$1.0 - 1.4$ kpc

[a]taken from Iijima & Esenoglu (2003)

[b]from extinction law of Rieke & Lebofsky (1985)

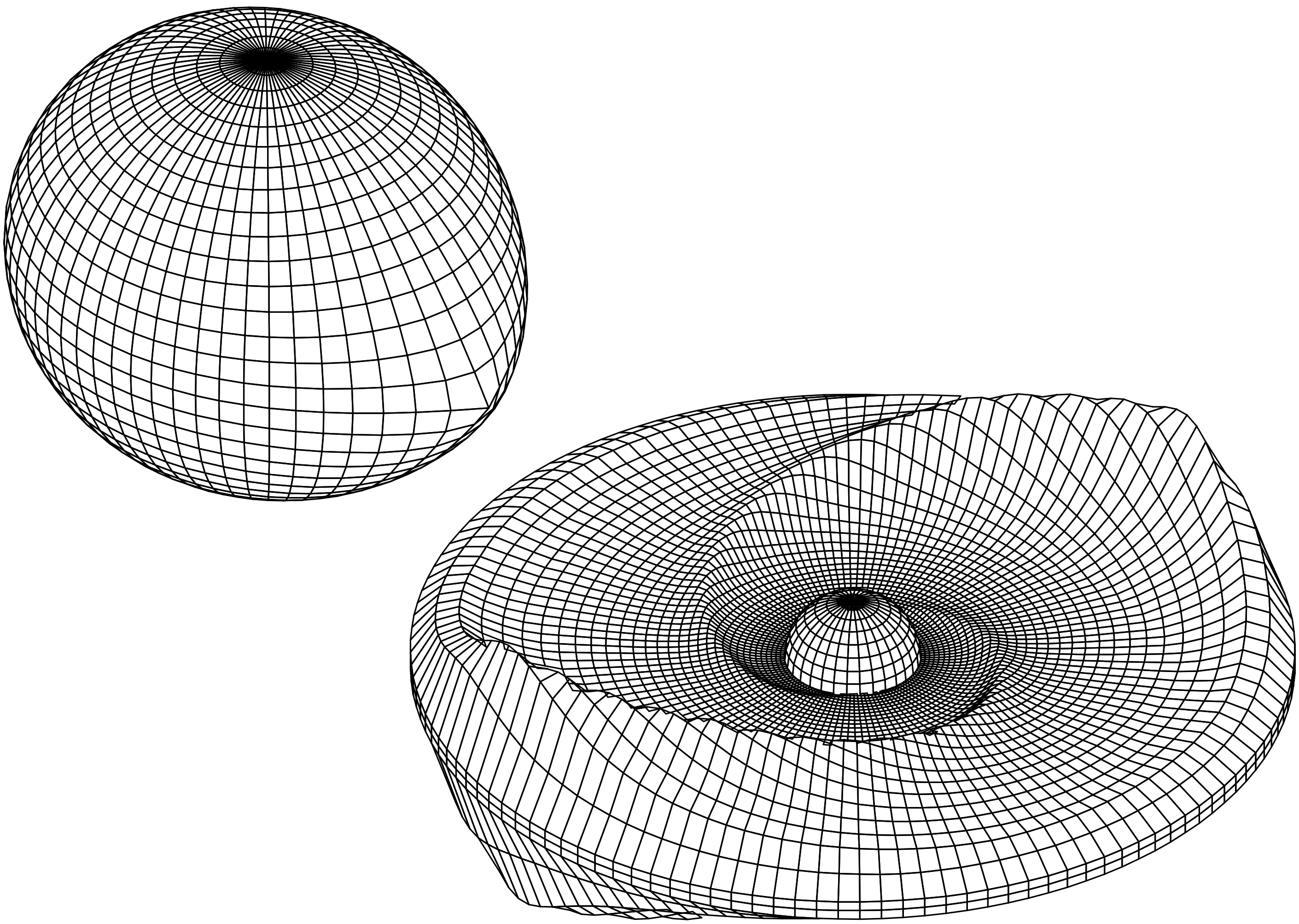

Fig. 1.— Our V1494 Aql model is illustrated. The cool component (*far and left side*) is an MS companion (0.3 $M_{\odot}$) filling up its inner critical Roche lobe. The north and south polar areas of the cool component are irradiated by the hot component (1.0 $M_{\odot}$ WD, *near and right side*). The separation is $a = 1.21\ R_{\odot}$; the effective radii of the inner critical Roche lobes are $R_1^* = 0.59\ R_{\odot}$, and $R_2^* = R_2 = 0.34\ R_{\odot}$, for the primary WD and the secondary MS companion, respectively. A two-armed spiral pattern is shown on the accretion disk. The WD surface is artificially enlarged to easily see it.

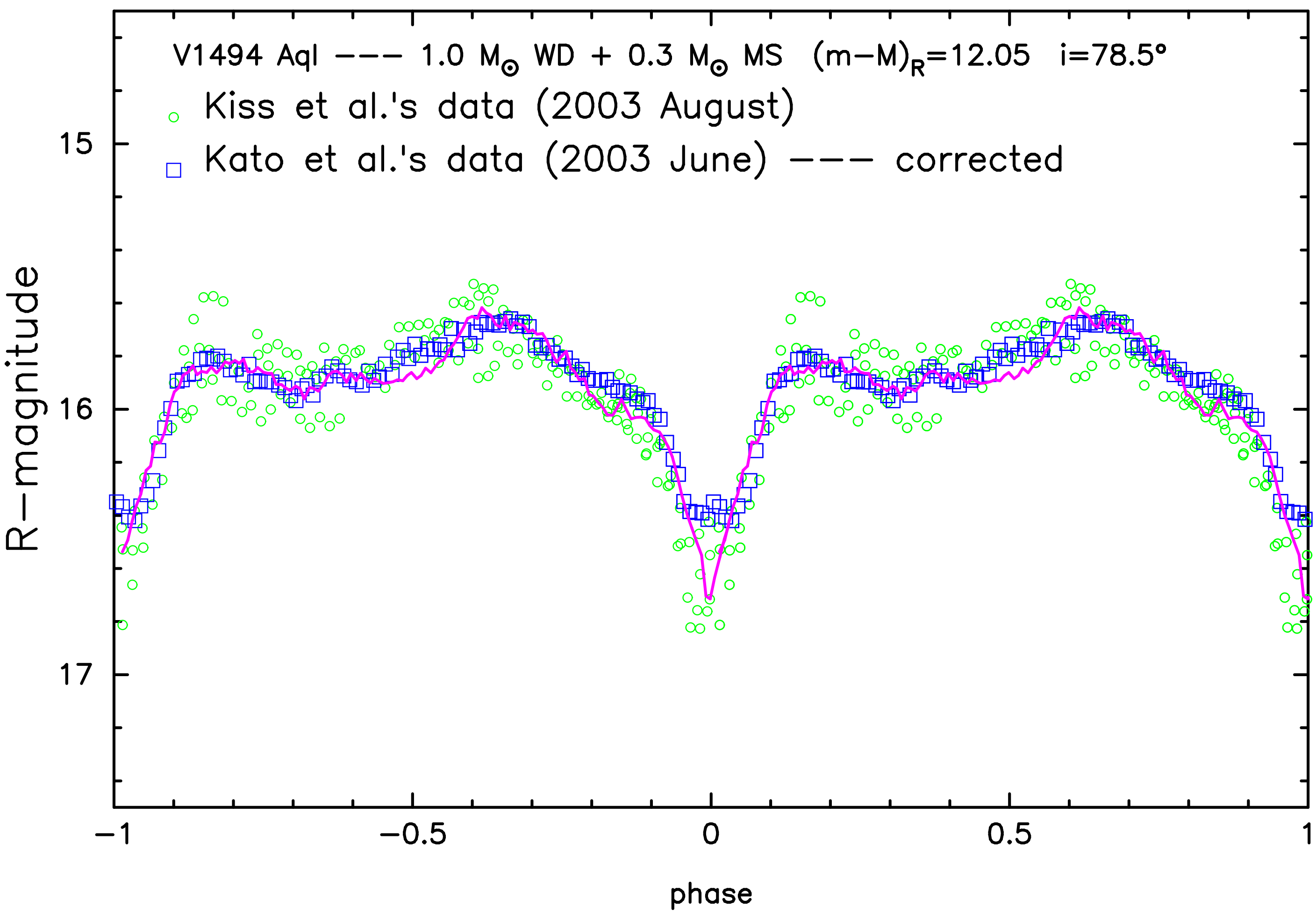

FIG. 2.— Calculated R_c light curves are plotted against the binary phase (binary phase is repeated twice from −1.0 to 1.0) together with the observational points of Kato et al. (2004, square) and of Kiss et al. (2004, circle). A thick solid line denotes R_c light curve for the best fit model. The apparent distance modulus is $(m-M)_R = 12.05$ for the WD luminosity of $L_{\rm WD} = 3,000\ L_\odot$. The adopted system parameters are listed in Table 1.

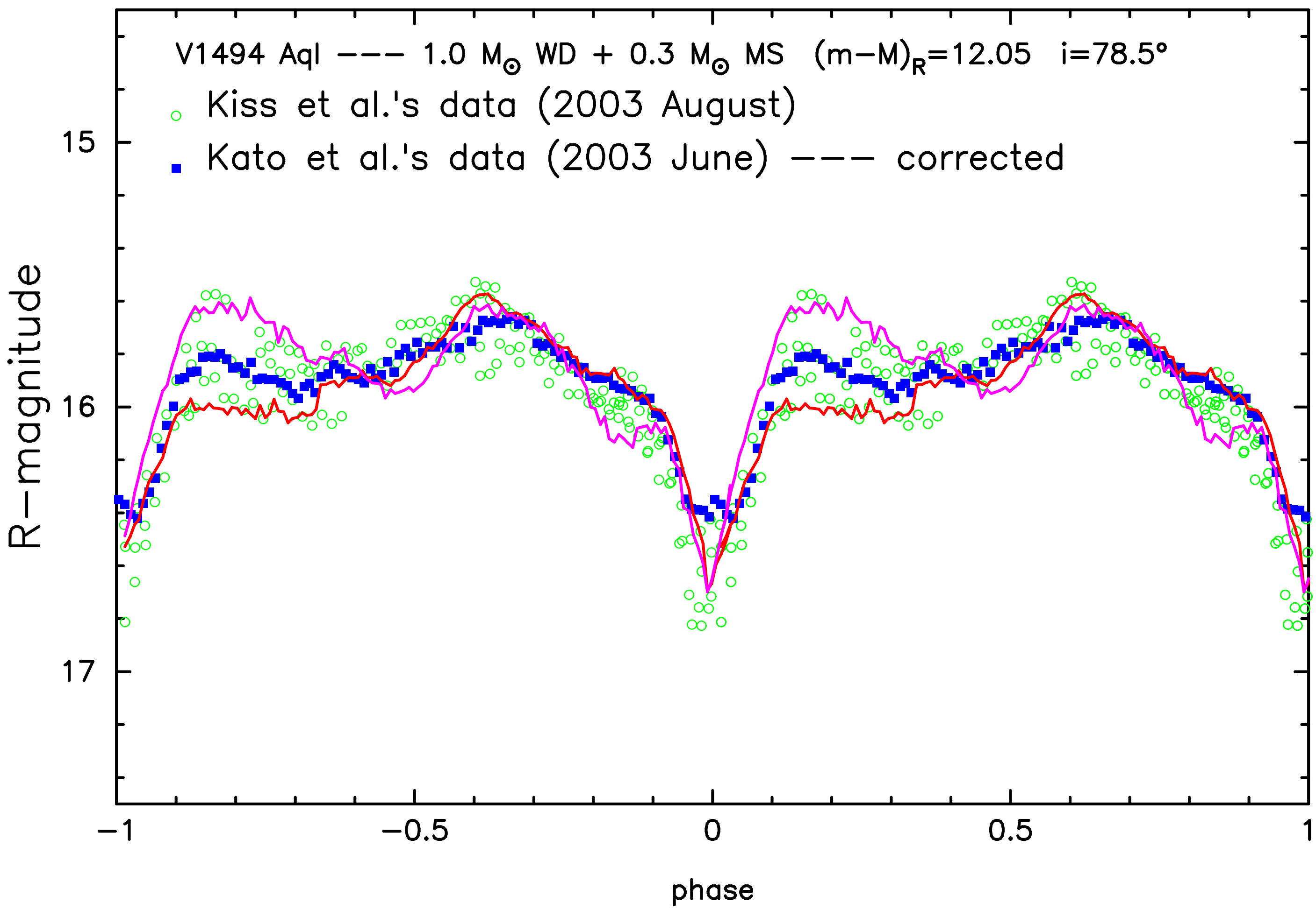

FIG. 3.— Same as in Fig. 2 but for variations of numerical models with different heights of spirals. The variations appear at orbital phase of $0.1 - 0.3$ but the peak at phase $\sim 0.6 - 0.7$ is robust. See text for details.